LEPA AND SPRAY IRRIGATION FOR GRAIN CROPS[a]

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ABSTRACT: Two low energy precision application (LEPA) sprinkler methods (double-ended socks and bubblers) and two spray sprinkler methods (low-elevation spray application and overhead spray) were used to irrigate corn, grain sorghum, and winter wheat in the Southern High Plains. For full or 100% irrigation, sufficient 25-mm applications were applied to maintain soil water at non-yield-limiting levels determined in earlier research with the three crops. Deficit-irrigated treatments were irrigated on the same days as the control treatment in 25 or 33% increments of the fully irrigated amount. Irrigation water was applied to or above alternate furrows with a three-span lateral move irrigation system. Corn and sorghum were grown on beds and furrows with all furrows diked, and wheat was flat-planted without basin tillage. Grain yields increased significantly with irrigation amount ($p \leq 0.05$) for all crops during all years. With full irrigation, grain yields varied little among the sprinkler methods, and yields averaged 13.5, 8.9, and 4.6 Mg/ha for corn, sorghum, and wheat, respectively. With the 25 and 50% deficit irrigation amounts, sorghum yields with LEPA irrigation were 1.1 Mg/ha larger than with the two spray methods. For 75% irrigation of sorghum and for deficit irrigation of the other two crops, there was little yield difference between the LEPA and spray sprinkler methods. Grain yields were significantly correlated with seasonal water use with regression coefficients of 2.89, 1.84, and 0.915 kg/m^3 for corn, sorghum, and wheat, respectively.

INTRODUCTION

In the Southern High Plains, a major transition from furrow to sprinkler irrigation has been underway since the late 1950s (Musick et al. 1990). The impact sprinklers initially used on center-pivot irrigation systems have largely been replaced by spray heads having higher application efficiencies (Musick et al. 1988). More recently, the low energy precision application (LEPA) sprinkler method was developed by Lyle and Bordovsky (1981) to increase application efficiencies in the 95–98% range. In on-farm evaluations with equal amounts of water, Fipps and New (1990) measured larger crop yields with LEPA than with other sprinkler methods (type of sprinkler method not reported).

When compared with spray irrigation, LEPA eliminates droplet evaporation and drift and crop canopy evaporation and reduces soil evaporation, particularly when irrigating alternate furrows. For 123 center-pivot irrigation systems equipped with spray heads, Musick et al. (1988) reported an average application efficiency of 85% based on the sprinkler catch in oil cans. For LEPA irrigation, Lyle and Bordovsky (1983) measured an application efficiency of 99% with catch containers when averaged over 24 irrigations. Similarly, Schneider and Howell (1990) reported LEPA application efficiencies of 96–98% measured with 9-m^2 weighing lysimeters.

Although the reported application efficiencies for LEPA irrigation are 10% or more larger than for spray irrigation, the on-farm efficiency of the two sprinkler methods may be nearly equal. Runoff from high-flow LEPA devices may either redistribute water within the field or leave the field completely. For example, Buchleiter (1992) measured runoff amounts exceeding 30 and 55% of the applied water on 3 and 8% slopes, respectively. Spurgeon et al. (1995) compared the LEPA bubble and flat (in-canopy) spray sprinkler methods on a Ulysses silt loam soil with soil surface modification and slopes ranging from 0.3 to 6.9%. The linear regression model developed from their data predicted equal grain yields by both sprinkler methods with zero slope but larger yield reductions due to slope for the LEPA method than the flat spray method.

Recent studies indicate smaller evaporation losses from sprinkler and spray irrigation than suggested by the earlier work of Christiansen (1942) and Frost and Schwalen (1955). In a laboratory study, Kincaid and Longley (1989) found that the evaporation rate of 1.0-mm-diameter droplets subjected to the high evaporative environment of 31°C and 22% relative humidity did not exceed 1% of the mass per second. Solomon et al. (1985) showed that the average droplet size from serrated spray plates exceeds 1.0 mm. With in-air times <1 s, droplet evaporation with serrated spray plates would then be expected to be 2% or less. This estimate is supported by Kohl et al. (1987) who measured low-pressure sprinkler losses of 0.5–1.4% from smooth spray plates and 0.4–0.5% from coarse, serrated spray plates. Modeling studies by Thompson et al. (1993, 1997) showed a total droplet evaporation loss of 3% from a solid set sprinkler system and 1% from a moving lateral irrigation system. For a mature corn canopy, Tolk et al. (1995) showed that, after accounting for microclimate modification and transpiration suppression due to evaporation of canopy-intercepted water, net canopy evaporation losses ranged from 5.1 to 7.1%.

Although considerable data are available for both the LEPA and spray sprinkler methods, field studies comparing LEPA with high-efficiency spray irrigation are limited. Howell and Phene (1983) measured the lint yield of cotton irrigated with trickle drag lines similar to LEPA and overhead spray. Lint yields from a single, fully-irrigated crop were 613 and 688 kg/ha for the trickle drag lines and spray, respectively. In the field study of Spurgeon et al. (1995), the yield reduction due to slope with fully irrigated corn was 1.48 Mg/ha/%slope with the LEPA bubble method and 0.73 Mg/ha/%slope with the flat (in-canopy) spray method. The original LEPA evaluation (Lyle and Bordovsky 1983) was a comparison between LEPA and impact sprinklers and did not include spray irrigation. In their 6-year summary of LEPA irrigation in Texas, Fipps and New (1990) did not list the type of conventional sprinkler methods used in the center-pivot comparisons. Their LEPA devices were located in the span nearest the outer span, and Fangmeier et al. (1990) showed that outer spans have better uniformity than the interior ones.

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In the field studies summarized here, a comparison was made of the effect of LEPA and spray sprinkler methods and irrigation amount on grain yields and water use efficiency (WUE) of corn, grain sorghum, and winter wheat grown in the Southern High Plains environment.

PROCEDURE

Experimental Site

The research was conducted on a 120-m-wide by 660-m-long field divided into four, 165-m-long experimental blocks at the USDA Conservation and Production Research Laboratory, Bushland, Tex. (35°11′ N, 102°06′ W, 1,170-m mean sea level elevation). The soil is Pullman clay loam, a fine, mixed, thermic, torrertic Paulestoll, with a dense B21t subsoil from about 0.15–0.40 m and a calcic horizon at depths of 1.5–2.0 m (Unger and Pringle 1981). The field has a uniform slope of about 0.0025 m/m in the direction of travel of the lateral move irrigation system and a 0.0022 m/m cross slope. The cropping years were 1992–1993 for sorghum and 1994–1995 for corn and wheat.

Experimental Design

The LEPA and spray sprinkler methods were evaluated with an irrigation control treatment receiving 100% of soil water replenishment and three or four deficit irrigation treatments that received a percentage of the control treatment application on the same date. Soil water levels for maximum grain production were determined in earlier irrigation research at the laboratory. The deficit irrigation percentages were 0, 25, 50, and 75% for corn; 25, 50, and 75% for sorghum; and 0, 33, and 67% for wheat. Field plots were arranged in a randomized block experimental design with the irrigation amounts being the blocks and the sprinkler methods being randomized within each of three replicates. Irrigation plots were 9.12 m wide (12 rows, each 0.76 m wide) along the irrigation system and 25 m long in the direction of travel.

The two LEPA sprinkler methods were double-ended socks and bubble applicators (Fangmeier et al. 1990; Fipps and New 1990), and the two spray methods were low elevation spray application (LESA) and overhead spray. LEPA double-ended socks were pulled along alternate furrows, and LEPA bubble applicators were positioned about 0.3 m above ground level. LESA spray heads were also positioned about 0.3 m above ground, and overhead spray heads were located about 0.3 m above the mature crop height. LESA was not used with wheat because of the difficulty of spraying water through the dense wheat canopy.

Gravimetric and neutron soil water measurements provided data for growing season soil water depletion, estimation of seasonal evapotranspiration, and irrigation scheduling. To calculate seasonal soil water depletion, all corn and wheat plots were gravimetrically sampled in 0.3-m increments to a depth of 1.8 m at planting and after harvesting. To schedule irrigations, soil water was measured weekly with a neutron probe in the three plots being fully irrigated with LEPA double-ended socks. Irrigations were applied to maintain available plant soil water above 90% in the 1.5-m profile for corn, above 75% in the 1.4-m profile for sorghum, and above 70% in the 1.0-m profile for wheat. The neutron soil water meter (CPN Model 503DR) was field calibrated at the laboratory (Evett and Steiner 1995).

Irrigation Equipment

Irrigations were applied with a hose-fed, Valmont Model 6000 lateral move irrigation system equipped with a computerized control panel. The lateral move system had three spans (39 m long), each providing space for 48 beds (0.76 m wide) and furrows. With the computerized speed control, irrigation amount was varied by varying the percent of each minute that the irrigation system moved. With the four-tower system, the two end towers and two interior towers all moved every minute for all irrigation amounts. Table 1 lists the LEPA and spray sprinkler application devices. All application devices were spaced 1.52 m apart above alternate furrows and discharged 19.0 L/min. Pressure to all application devices was 207 kPA, but 41- and 69-kPa pressure regulators were used as listed in Table 1. The LEPA socks (A. E. Quest & Sons) were attached to Senninger Super Spray heads. When the Nelson Spray I spray heads were equipped with 69-kPa pressure regulators, 5.9- and 6.1-mm nozzles were alternated to obtain an average 19.0 L/min per spray head from the overhead spray. Medium-grooved, convex spray plates were used with the Nelson Spray I spray heads. Both the LEPA and spray devices were suspended from 0.38-m-long furrow arms that were individually rotated as needed to center the sprinkler devices over alternate furrows. All furrows in the corn and sorghum fields were diked, and the first irrigation of the growing season was applied with overhead spray only to consolidate the soil forming the furrow dikes. No furrow dike maintenance was done so the dikes eroded and washed out similar to those on large, on-farm fields. Irrigation runoff was retained on individual plots with dikes so that runoff was redistributed but not lost.

TABLE 1. Irrigation Application Devices

Sprinkler device (1)	Manufacturer (2)	Model (3)	Pressure (kPa) (4)	Nozzle diameter (mm) (5)
LEPA sock	A. E. Quest & Sons and Senninger	Super Spray	207[a] 41[b]	4.8 6.8
LEPA bubble	Senninger	Quad IV	41	6.8
LESA	Senninger	Quad IV	41	6.8
Overhead spray	Nelson	Spray I	207[c] 69[d]	4.6 5.9 and 6.1

[a]Grain sorghum.
[b]Corn and wheat.
[c]Grain sorghum and 1994 wheat crop.
[d]Corn and 1995 wheat crop.

Cultural Practices

The grain crops were grown with cultural practices (variety, fertility, plant population, and weed and insect control) similar to those used for high-yield management on commercial farms. All crops were grown on land that had been fallowed during the previous year to increase soil water levels at planting time and to hopefully reduce weed, insect, and pathogen populations. Crop residues were shredded as necessary, and tandem disking was used for primary tillage. For corn and sorghum, 0.76-m-spaced beds were formed with a disk bedder, and the crops were planted with a John Deere MaxEmerge planter. The row crops were cultivated when the plants were 0.15–0.25 m high, and furrows were diked before the first growing season irrigation. Wheat was flat-planted in 0.25-m-spaced rows with a Tye grain drill. No reservoir tillage was used to retain runoff from the wheat, but dikes retained runoff along the lower ends of the plots.

Sufficient nitrogen and phosphorus fertilizer was applied to fully utilize the yield potential of the applied irrigation water. The two corn crops initially received 80 and 110 kg(N)/ha from preplant anhydrous ammonia. Later in the growing season, the 100% irrigation treatments received 100 and 90 kg(N)/ha from urea injected into the irrigation water, and the deficit-irrigated treatments received proportionately less. Both sorghum crops received 112 kg(N)/ha, and the wheat crops received 110 and 135 kg(N)/ha—all as preplant anhydrous ammonia. The Pullman clay loam soil has a high inherent phosphorus fertility level, and applied phosphorus is not leached from the soil. For this reason, a uniform 112 kg(P)/ha phosphorus application was made for all crops during 1992. Soil fertility analyses showed that the Pullman soil contained sufficient potash for maximum grain yields. Atrazine was applied for broadleaf weed control in the corn and sorghum, and a mixture of Capture and dimethoate was applied for corn borer control in 1994.

Corn grain yields were determined by hand harvesting 10-m^2 areas from each plot, drying the samples to zero water content, shelling the corn from the cobs, and weighing the corn and cobs. Sorghum and wheat grain yields were measured by harvesting two full lengths of each plot with a Hege plot combine having a 1.52-m-wide header. After weighing these samples, subsamples were dried to measure grain moisture content. Grain yields reported here are at 15.5, 14.0, and 13.0% moisture content by wet weight for corn, sorghum, and wheat, respectively.

RESULTS

The data reported here are a summary of 6 years of data—two crop years with each of the three grain crops. Other field studies comparing LEPA and spray irrigation of grain crops with a range of irrigation amounts are not known to exist. For this reason, the three studies have been summarized, and general recommendations are made for LEPA and spray irrigation in the Southern High Plains. Detailed results for three crops have been reported in Schneider and Howell (1995a,b, 1997, 1998).

Monthly rainfall and minimum and maximum temperatures—the most important climatic variables affecting grain production in the Southern High Plains—are illustrated in Figs. 1 and 2. The 1992 sorghum season was exceptional with 193 mm of rainfall during June alone and above average rainfall throughout the May–August interval. Even though the 100 mm of rainfall during July 1993 made the sorghum season near-average, the below average April–June rainfall made the deficit-irrigated treatments less effective. Winter and early-spring rainfall was near average for the 1994 wheat crop but well below average for the 1995 crop. The 115 mm of rainfall during May 1995 occurred too late to be fully utilized by the deficit-irrigated wheat and too early to have a major impact on the corn crop. For corn, the most beneficial rainfall was the 124 mm received during July 1994. Monthly maximum temperature for the 1992 sorghum season was below average for the four months during which rainfall was above average. For corn, the maximum temperature during June 1994 was 3.5°C above average, but the high temperatures occurred before the critical pollination growth stage. In contrast, the maximum temperature during August 1995 was only 0.9°C above average, but most of the high temperatures occurred during a 1-week interval and adversely affected corn pollination.

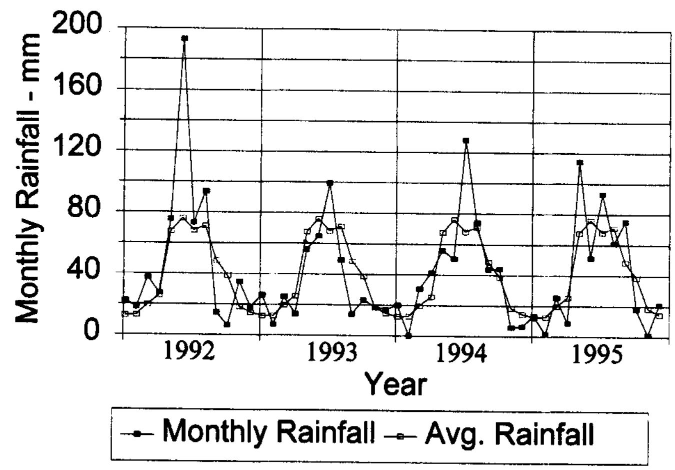

FIG. 1. Monthly Rainfall during Study Years and 58-Year Average Monthly Rainfall

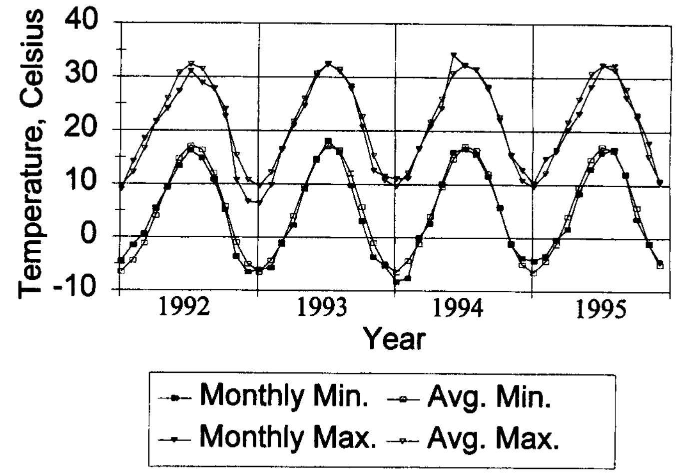

FIG. 2. Minimum and Maximum Monthly Temperatures during Study Years and 58-Year Average Minimum and Maximum Monthly Temperatures

The dates of all irrigations applied during the six crop years are listed in Table 2. With all crops grown on previously fallowed land, preseason irrigation was generally not needed, but most crops required an emergence irrigation. The 1994 corn crop received only a 30-mm emergence irrigation, but the 1995 corn crop required both 44 mm of preseason irrigation and 28 mm of emergence irrigation. For the 100%-irrigated treatments, the 1994 corn crop received 513 mm of irrigation in 21 seasonal applications, and the 1995 crop received 550 mm of irrigation in 22 seasonal applications. The 1992 sorghum crop was established with stored soil water and rainfall, but the 1993 crop received an 18-mm emergence irrigation. Seasonal sorghum irrigation totals for the 100%-irrigated treatments were 250 and 325 mm for the two respective years. The 1994 wheat crop received a 25-mm emergence irrigation, and the 100%-irrigated treatments then received 350-mm of spring irrigation. Rainfall was sufficient to establish the 1995 wheat crop, but with drier soil conditions, all treatments received a 19-mm fall irrigation and two 25-mm winter irrigations. The 100%-irrigated wheat received 375 mm of irrigation during the spring of 1995.

Grain Yields

Grain yields increased significantly ($p \leq 0.05$) with irrigation amount for each of the three crops (Fig. 3), but the distribution of yield increases varied from crop to crop. Average corn yields with 25% irrigation were depressed by the zero yields in 1995. As a result, the average yield increase with 25% irrigation was only 1.72 Mg/ha, but the yield increase from 25 to 50% irrigation was 6.47 Mg/ha. Further yield increases of 3.28 and 2.02 Mg/ha occurred with increases to 75 and 100% irrigation, respectively. The yield curves in Fig. 3 suggest that corn yields might continue to increase beyond the 100% irrigation level. The soil water data presented by Schneider and Howell (1998), however, suggest that other factors such as high temperatures during pollination might be limiting maximum yields. Corn yield as a function of seasonal water use was highly significant with a regression slope of 2.89 kg/m^3 (Schneider and Howell 1998). The regression analysis also indicated a threshold seasonal water use for grain production of 301 mm. With sorghum, the average yield in-

TABLE 2. Irrigation Dates for Six Crop Years[a]

Month (1)	1992 sorghum (2)	1993 sorghum (3)	1994 wheat (4)	1995 wheat (5)	1994 corn (6)	1995 corn (7)
October			12	31 (19 mm)		
December				2		
February				2		
March			23	21 23 27		
April			1 8 15 21	6 12 14 18 21 27	18 (30 mm)	19 21 (19 mm)
May		2 (18 mm)	6 9 12 16 19 31	1 4 12 16 19 23		1 (20 mm) 9 (8 mm)
June		30	2 7 9		5 8 12 15 17 (19 mm) 19 (19 mm) 22 24 28	15 20 23 26
July	9 17 22 31	2 6 9 13 25 30			1 3 5 7 12 20 24 27	1 8 11 14 18 24 26 29
August	4 7 12 14	14 18 21 24 27			8 12 17 22	1 4 8 13 18 22 25 28
September	4 11	1				1 4

Note: Numbers in Columns 2–7 signify day of month.
[a]All irrigations to 100%-irrigated treatments were 25 mm unless otherwise noted in parentheses following day of month.

crease from 25 to 50% irrigation was 2.47 Mg/ha, but yield increases for the two larger irrigation increments were only 0.59 and 0.60 Mg/ha, respectively. Sorghum yields and seasonal water use were also significantly correlated with a regression slope of 1.84 kg/m^3 (Schneider and Howell 1995a). Wheat yields increased throughout the range of irrigation, but the yield increments decreased with increasing irrigation amount. The 0–33% yield increase was 1.31 Mg/ha, but increases to 67 and 100% irrigation only increased yields 0.94 and 0.45 Mg/ha, respectively. With the small yield increment from 67 to 100% irrigation, only the deficit-irrigated wheat

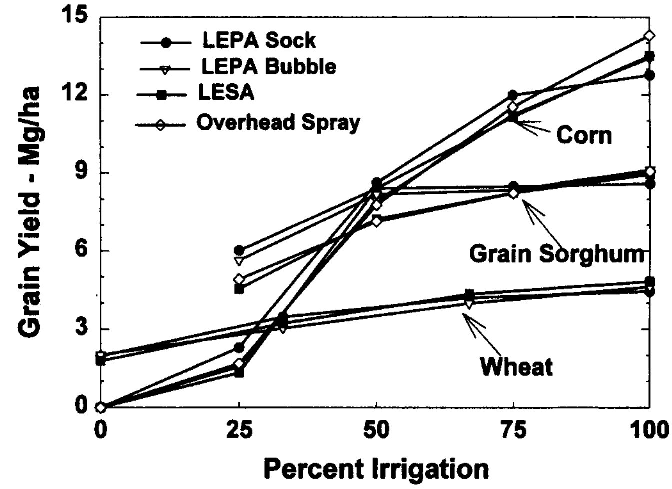

FIG. 3. Two-Year Average Corn, Grain, Sorghum, and Winter Wheat Grain Yields

yields were significantly correlated with seasonal water use with the regression slope being 0.915 kg/m^3 (Schneider and Howell 1997).

Yield differences between either the LEPA sock and bubble methods or the LESA and overhead spray methods were small and generally not statistically significant ($p \leq 0.05$). The main comparison here is between the LEPA and spray sprinkler methods. With corn, yields with the LEPA sock method were slightly larger at the three intermediate irrigation amounts but with 100% irrigation were 0.98 Mg/ha less than the average for the other three sprinkler methods. It is thought that this lower yield with 100% irrigation is due to random variability in field yields and sampling error rather than to a real treatment effect. For the 25 and 50% irrigation of sorghum, yield increases of 1.10 and 1.11 Mg/ha with LEPA made the LEPA yields significantly larger ($p \leq 0.05$) than with spray. For 75% irrigation, the yields were still 0.18 Mg/ha larger with the LEPA methods, but with 100% irrigation, yields with the spray methods were 0.15 Mg/ha larger. Wheat yields with the LEPA methods were only 0.03 Mg/ha larger than spray with 33% irrigation. For the two larger irrigation amounts, the yield with overhead spray exceeded that with the LEPA methods by 0.25 and 0.29 Mg/ha, respectively.

WUE

WUEs for the three crops are listed in Table 3. Seasonal WUE is defined as grain yield divided by seasonal water use, and irrigation water use efficiency (IWUE) is defined as grain yield minus the zero-irrigated grain yield divided by seasonal irrigation amount. Because of the zero corn yields with 0 and 25% irrigation, the corn WUEs for the three larger irrigation amounts are more meaningful. For 50 to 100% irrigation of corn, WUE ranged from 1.31 to 1.78 kg/m^3, and IWUE ranged from 2.43 to 3.08 kg/m^3. In general, the larger WUEs occur with 75 to 100% irrigation, and the larger IWUEs occur with 50% irrigation. For corn, there were no major WUE or IWUE differences among the four sprinkler methods.

For sorghum, data were only available to calculate WUE for the LEPA bubble and overhead spray sprinkler methods. For the 25 and 50% irrigation amounts, WUE with the LEPA sock sprinkler method exceeded that with overhead spray by about 0.2 kg/m^3. And for both sprinkler methods, WUE increased about 0.35 kg/m^3 from the 25% to the 50% irrigation amount. With the two larger irrigation amounts, there was little variability in WUE between irrigation amount or sprinkler method.

For wheat, WUE ranged from 0.51 to 0.76 kg/m^3, and IWUE ranged from 0.70 to 1.01 kg/m^3. For all sprinkler meth-

TABLE 3. Two-Year Average Seasonal Water Use, Seasonal WUE, and IWUE

	LEPA Sock			LEPA Bubble			LESA			Overhead Spray		
Percent irrigation (1)	Water use (mm) (2)	WUE (kg/m³) (3)	IWUE (kg/m³) (4)	Water use (mm) (5)	WUE (kg/m³) (6)	IWUE (kg/m³) (7)	Water use (mm) (8)	WUE (kg/m³) (9)	IWUE (kg/m³) (10)	Water use (mm) (11)	WUE (kg/m³) (12)	IWUE (kg/m³) (13)
(*a*) Corn												
0	315	0	—	315	0	—	315	0	—	315	0	—
25	473	0.46	1.84	473	0.31	1.25	472	0.27	1.06	465	0.36	1.35
50	572	1.51	3.31	580	1.39	3.08	577	1.47	3.20	591	1.31	2.98
75	703	1.71	3.04	709	1.59	2.84	713	1.56	2.84	719	1.61	2.94
100	835	1.53	2.43	796	1.69	2.55	792	1.70	2.58	805	1.78	2.73
(*b*) Grain Sorghum												
25	427	1.41	—	—	—	—	398	1.22	—	—	—	—
50	478	1.76	—	—	—	—	458	1.55	—	—	—	—
75	547	1.55	—	—	—	—	545	1.51	—	—	—	—
100	584	1.47	—	—	—	—	585	1.55	—	—	—	—
(*c*) Wheat												
0	346	0.58	—	346	0.58	—	—	—	—	346	0.51	—
33	457	0.76	1.01	433	0.70	0.70	—	—	—	420	0.76	0.80
67	574	0.73	0.83	575	0.69	0.74	—	—	—	566	0.77	0.88
100	675	0.66	0.65	657	0.71	0.70	—	—	—	664	0.73	0.73

ods, WUE was lowest for zero irrigation, increased to the largest value at 33 or 67% irrigation, and then decreased slightly for 100% irrigation. However, there was little difference among the three sprinkler methods. The larger wheat IWUEs occurred with 33 or 67% irrigation for all sprinkler methods.

The 2-year average seasonal water use for the three crops is listed in Table 3. Seasonal water use of the 100%-irrigated corn ranged from 792 to 835 mm and was within the 744- to 901- mm evapotranspiration range measured by Howell et al. (1996) with weighing lysimeters at Bushland. For deficit-irrigated corn, seasonal water use did not vary appreciably among the sprinkler methods. For sorghum, seasonal water use by the 100%-irrigated sorghum was nearly identical to the 578 mm measured by Howell et al. (1997). With 25 and 50% irrigation, seasonal water use was 29 and 20 mm larger, respectively, with the LEPA sock method than the overhead spray method due to increased soil water depletion. It is speculated that the alternate furrow LEPA irrigation permitted deeper wetting and root development and hence a greater ability to deplete the soil water reservoir. For all irrigation amounts, seasonal water use by wheat was larger with the LEPA methods than with overhead spray. This did not, however, result in larger yields or WUE by the LEPA irrigated wheat.

With 100% irrigation, 2-year average grain yields were slightly larger with the spray methods than with the LEPA methods, but the differences were small. The 2-year average yields of corn were 13.9 Mg/ha with the spray methods and 13.1 Mg/ha with the LEPA methods. Comparable yields with sorghum were 9.00 and 8.85 Mg/ha, respectively. With wheat the comparable yields were 4.82 Mg/ha with overhead spray and 4.53 Mg/ha with the two LEPA methods. In irrigation amount studies in the Southern High Plains, grain yields in the 80–120% irrigation range are generally about equal. The increased application efficiency of LEPA over spray irrigation will typically not exceed 8–10%. Thus, with 100% irrigation, the irrigation application efficiencies with the LEPA method were not sufficiently larger than with the spray method to result in larger grain yields.

The large sorghum yields with 25 and 50% LEPA irrigation illustrate the potential for deficit LEPA irrigation of drought-tolerant crops. In 1992 with 125 mm of seasonal irrigation, the sorghum yield with the LEPA sock method was a near maximum 9.31 Mg/ha (Schneider and Howell 1995a,b) and exceeded that of the overhead spray method by 1.44 Mg/ha. With 75% irrigation, the LEPA sock yield of 9.21 Mg/ha still exceeded the overhead spray yield by 0.75 Mg/ha. With 100% irrigation, the LEPA advantage disappeared, and the overhead spray yield of 9.52 Mg/ha exceeded that of the LEPA sock by 0.35 Mg/ha.

With deficit irrigation of corn and wheat, however, there were no significant yield differences between the LEPA and spray sprinkler methods. Corn yields with the LEPA sock method were slightly larger than with the other three sprinkler methods, but the differences were small. It is thought that the lack of response to deficit LEPA irrigation of wheat may be due to the nonuniform LEPA water distribution. In the 33%-irrigated plots and to some extent in the 67%-irrigated plots, the wheat plants were shorter midway between the LEPA drops than beneath the drops.

Runoff occurred from the 100% LEPA-irrigated plots of all three crops, particularly late in the growing season. Less severe runoff also occurred from the 75%-irrigated corn plots. This runoff occurred even with the furrow dikes that were gradually eroded by the multiple irrigations during the growing season. All irrigation water was retained on the plots with dikes, but on the LEPA-irrigated plots, this water was not uniformly distributed.

CONCLUSIONS

With 100% irrigation, grain yields of corn, grain sorghum, and winter wheat were nearly equal with the LEPA and spray sprinkler methods. The LEPA method was more efficient for deficit irrigation of sorghum, increasing the grain yields with 25 and 50% irrigation by 1.1 Mg/ha over the spray methods. With deficit irrigation of corn and winter wheat, however, grain yields with the LEPA and spray sprinkler methods were also nearly equal. Although the application efficiency of the LEPA method is larger than that of the spray method, grain yields with the two sprinkler methods and 100% irrigation tend to be about the same.

APPENDIX. REFERENCES

Buchleiter, G. H. (1992). "Performance of LEPA equipment on center pivot machines." *Appl. Engrg. in Agric.*, 8(5), 631–637.

Christiansen, J. E. (1942). "Irrigation by sprinkling." *California Agric. Expt. Sta. Bull. No. 670*, University of California, Berkeley, Calif.

Evett, S. R., and Steiner, J. L. (1995). "Precision of neutron scattering and capacitance type soil water content gages from field calibration." *Soil. Sci. Soc. Am. J.*, 59(40), 961–968.

Fangmeier, D. D., Voltman, W. F., and Eftekharzadeh, S. (1990). "Uniformity of LEPA irrigation systems with furrow drops." *Trans. ASAE*, 33(6), 1907–1912.

Fipps, G., and New, L. L. (1990). "Six years of LEPA in Texas—less water, higher yields." *Proc., 3rd Nat. Irrig. Symp.*, American Society of Agricultural Engineers, Phoenix, 115–120.

Frost, K. R., and Schwalen, H. C. (1955). "Sprinkler evaporation losses." *Agric. Engrg.*, 36(8), 526–528.

Howell, T. A., Evett, S. R., Tolk, J. A., Schneider, A. D., and Steiner, J. L. (1996). "Evapotranspiration of corn—Southern High Plains." *Proc., Int. Conf., Evapotranspiration and Irrig. Scheduling*, C. R. Camp, E. J. Sadler, and R. E. Yoder, eds., American Society of Agricultural Engineers, San Antonio, 158–166.

Howell, T. A., and Phene, C. J. (1983). "Distribution of water from a low pressure lateral-moving irrigation system." *Trans. ASAE*, 26(5), 1422–1429, 1434.

Howell, T. A., Steiner, J. L., Schneider, A. D., Evett, S. R., and Tolk, J. A. (1997). "Seasonal and maximum daily evapotranspiration of irrigated winter wheat, sorghum and corn—Southern High Plains." *Trans. ASAE.*, 40(3), 623–634.

Kincaid, D. C., and Longley, T. S. (1989). "A water droplet evaporation and temperature model." *Trans. ASAE*, 32(2), 457–463.

Kohl, K. D., Kohl, R. A., and DeBoer, D. W. (1987). "Measurement of low pressure sprinkler evaporation loss." *Trans. ASAE*, 30(4), 1071–1074.

Lyle, W. M., and Bordovsky, J. P. (1981). "Low energy precision application (LEPA) irrigation system." *Trans. ASAE*, 24(5), 1241–1245.

Lyle, W. M., and Bordovsky, J. P. (1983). "LEPA irrigation system evaluation." *Trans. ASAE*, 26(3), 776–781.

Musick, J. T., Pringle, F. B., Harman, W. L., and Stewart, B. A. (1990). "Long-term irrigation trends—Texas High Plains." *Appl. Engrg. in Agric.*, 6(6), 717–724.

Musick, J. T., Pringle, F. B., and Walker, J. W. (1988). "Sprinkler and furrow irrigation trends—Texas High Plains." *Appl. Engrg. in Agric.*, 4(1), 46–52.

Schneider, A. D., and Howell, T. A. (1990). "Sprinkler efficiency measurement with large weighing lysimeters." *Proc., 3rd Nat. Irrig. Symp.*, American Society of Agricultural Engineers, Phoenix, 69–76.

Schneider, A. D., and Howell, T. A. (1995a). "Grain sorghum response to sprinkler application methods and system capacity." *Trans. ASAE*, 38(6), 1693–1697.

Schneider, A. D., and Howell, T. A. (1995b). "LEPA and spray irrigation in the Southern High Plains." *Water Resour. Engrg., Proc., 1st Int. Conf.*, Vol. 2, 1718–1722.

Schneider, A. D., and Howell, T. A. (1997). "Methods, amounts, and timing of sprinkler irrigation for winter wheat." *Trans. ASAE*, 40(1), 137–142.

Schneider, A. D., and Howell, T. A. (1998). "LEPA and spray irrigation of corn—Southern High Plains." *Trans. ASAE*, 41(5), 1391–1396.

Solomon, K. H., Kincaid, D. C., and Bezdek, J. C. (1985). "Drop size distributions for irrigation spray nozzles." *Trans. ASAE*, 28(6), 1966–1974.

Spurgeon, W. E., Feyerherm, A. M., and Manges, H. L. (1995). "In-canopy application mode and soil surface modification for corn." *Appl. Engrg. in Agric.*, 11(4), 517–522.

Thompson, A. L., Gilley, J. R., and Norman, J. M. (1993). "A sprinkler water droplet evaporation and plant canopy model: II. Model application." *Trans. ASAE*, 36(3), 743–750.

Thompson, A. L., Martin, D. L., Norman, J. M., Tolk, J. A., Howell, T. A., Gilley, J. R., and Schneider, A. D. (1997). "Testing of a water loss distribution model for moving sprinkler systems." *Trans. ASAE*, 40(1), 81–88.

Tolk, J. A., Howell, T. A., Steiner, J. L., Krieg, D. R., and Schneider, A. D. (1995). "Role of transpiration suppression by evaporation of intercepted water in improving irrigation efficiency." *Irrig. Sci.*, Berlin, 16, 89–95.

Unger, P. W., and Pringle, F. B. (1981). "Pullman soils: Distribution, importance & management." *Texas Agric. Expt. Sta. Bull. No. 1372*, Texas A&M University, College Station, Tex.